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Precise Global Observations from a Multi-frequency Passive Microwave Atmospheric Sounding Radiometer on a CubeSat: Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) 6U CubeSat Mission

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Global observations of clouds and precipitation are essential to improve monitoring and prediction of tropical cyclones and severe storms with substantial impacts on human life and property. To understand cloud and precipitation processes in different climate environments, rapid revisit global observations are necessary. To this end, geostationary satellites have improved weather prediction by providing visible and infrared measurements with temporal resolution on the order of a few minutes. However, to improve understanding of rapid, dynamic evolution of deep convection and surrounding water vapor, we require fine time-resolution millimeter-wave radiometric observations capable of penetrating deep inside the storm where the microphysical processes leading to precipitation occur.

To address this critical observational need, the Temporal Experiment for Storms and Tropical Systems (TEMPEST) mission deploys a closely-spaced train of 6U CubeSats carrying identical low-mass, low-power millimeter-wave radiometers. The TEMPEST train samples rapid changes in convection and water vapor by observing every 3-4 minutes for up to 30 minutes. The millimeter-wave radiometers on TEMPEST observe at five frequencies from 87 to 181 GHz, providing soundings of mid-tropospheric water vapor to improve understanding of its role in the growth and organization of convection. By rapidly sampling the life cycle of convection, TEMPEST fills a critical observational gap and complements existing and future satellite missions, e.g. TROPICS and GPM.

To demonstrate that such a train of 6U CubeSats has the capability to contribute to NASA Earth science goals, the TEMPEST Technology Demonstration (TEMPEST-D) mission was initiated as a partnership among Colorado State University (Lead Institution and validation), NASA/Caltech Jet Propulsion Laboratory (instrument and calibration) and Blue Canyon Technologies (spacecraft and mission operations). The TEMPEST-D satellite was launched on May 21, 2018 on Orbital ATK's ninth commercial resupply mission to the ISS and successfully deployed into orbit from the ISS by NanoRacks on July 13, 2018, from an initial orbit with 400-km altitude and 51.6° inclination to demonstrate that TEMPEST radiometer calibration and stability meets the needs of the TEMPEST investigation.

TEMPEST-D has met all mission requirements on schedule and within budget. After achieving first light on September 5, 2018, the TEMPEST-D mission has successfully achieved TRL 7 for both the instrument and spacecraft systems. TEMPEST-D performed its first full-swath orbital observations capturing Hurricane Florence over the Atlantic Ocean on September 11, 2018, revealing the eye of the storm surrounded by intense rain bands using a millimeter-wave radiometer on a CubeSat. TEMPEST-D is regularly acquiring nearly global five-frequency brightness temperature measurements each day, with downlink limited by ground station considerations for this technology demonstration mission.

TEMPEST-D brightness temperatures have been compared with those of four on-orbit reference sensors at similar frequencies, i.e. NASA/JAXA Global Precipitation Mission Microwave Imager (GMI) and Microwave

Humidity Sounders (MHS) on NOAA and EUMETSAT operational meteorological satellites. Results demonstrate cross-calibration of TEMPEST-D radiometer measurements with reference sensors with high accuracy and precision, indicating that TEMPEST-D is a very well-calibrated and stable radiometer with very low noise, rivaling that of much larger, more expensive operational instruments.